PB-217 922

A STUDY OF TIDAL DISPERSION IN THE POTOMAC RIVER

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Federal Water Pollution Control Administration
Charlottesville, Virginia

1965

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CB-SRBP Technical Paper No. 7
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A STUDY OF TIDAL DISPERSION IN THE POTOMAC RIVER

BY

L. J. Hetling and R. L. O'Connell

INTRODUCTION

The Chesapeake Bay-Susquehanna River Basins Project of the Federal Water Pollution Control Administration, U. S. Department of Health, Education, and Welfare has as its primary objective the development of a comprehensive program for water pollution control in the Chesapeake Bay drainage basin. The 14,170-square mile Potomac River Basin, second in size only to that of the Susquehanna River (27,000 square miles) in this drainage area, possesses a variety of water pollution problems which are most significant perhaps in that portion of the tidal estuary near Washington, D. C. (Figure 1). To permit a better understanding of this complex body of water and to provide a satisfactory means for analysis of present and future pollution problems and selection of optimum control methods, an attempt has been made to model the system in mathematical terms.

To mathematically describe the fate of pollutants entering such a tidal system, knowledge of its turbulent dispersion properties is required. To gather this type of information for the upper Potomac estuary, a dye tracer study was carried out by the Project during the 34-day period from June 10 to July 14, 1965.

Next page

The purpose of this report is to describe the procedure used in this large scale tracer experiment, the results obtained, the methods used in the analysis of these results, and, finally, to present the conclusions reached regarding turbulent dispersion properties of this tidal system.

THE SEGMENTED ESTUARY MODEL

The mathematical model employed in this study was that developed by Thomann.[7] This model consists of a system of "n" equations, each describing a mass balance of the material being studied for each of the "n" segments of an estuary. For an estuary where good vertical and lateral mixing may be assumed, these segments are selected along the longitudinal axis of the estuary. The segmentation of the Potomac estuary, as used in this tracer study, is shown in Figure 1.

The mass balance over each of the 16 segments shown in Figure 1 includes terms describing changes in dye concentration caused by advection, dispersion, losses, and, in the case of the segment to which the dye was added, a dye source. A mass balance constructed for the "i" th segment takes the form:

$$V_i \frac{dC_i}{dt} = Q_i [\xi_i C_{i-1} + (1 - \xi_i) C_i]$$

$$-Q_{i+1} [\xi_{i+1} C_i + (1 - \xi_{i+1}) C_{i+1}]$$

$$+E_i (C_{i-1} - C_i) + E_{i+1} (C_i - C_{i+1})$$

$$-d V_i C_i + P_i \qquad (1)$$

where

V_i = volume of "i" th segment, cubic feet (cf)

C_i = mean dye concentration in "i" th segment (lb/cf)

Q_i = net waterflow across the upstream boundary of the "i" th segment (cf/day)

ξ_i = a dimensionless proportionality factor used to estimate concentration at upper boundary of the "i" th segment

E_i = turbulent exchange factor for upstream boundary of the "i" th segment (cf/day)

d = dye loss rate constant (day^{-1})

P_i = rate of dye addition from external source (lbs/day)

t = time (days)

Since for this study sixteen estuary segments were employed, a like number of expressions similar to equation (1) was obtained. This system of sixteen linear first order, non-homogeneous, ordinary differential equations may be solved simultaneously by numerical methods using a digital computer or by programing the equations on a relatively large analog computer. In either case, all terms of the equations must be known in order to solve for the dye concentration of each segment as a function of time. In this dispersion experiment, however, the segment concentrations were known from the results of sampling the estuary, while the turbulent exchange factor, "E", for each segment was unknown. It was necessary, therefore, to solve for the "E_i's" by trial and error methods. By this procedure, initial values for "E_i" were chosen and a solution for "C_i" obtained. The calculated concentrations were then compared with observed values, suitable adjustments made to the "E_i" values and a new solution for "C_i" found. This process was repeated until a satisfactory agreement between observed and calculated concentrations was found. Because of the repetitive calculation-comparison process required, analysis by analog computer was considered to be the most efficacious method for obtaining a solution in this case.

In the following sections, each of the terms of equation (1) is discussed in terms of the dye tracer experiment.

TEST CONDITIONS

Dye Source (P_i)

A dye was released into estuary segment 5 via the outfall sewer of the District of Columbia Water Pollution Control Plant (Blue Plains). This outfall consists of two parallel 90-inch diameter lines and extends 900 feet into the estuary from the eastern shore, terminating at the eastern edge of the shipping channel in about 17 feet of water at mean tide level (MTL). The dye used was Rhodamine WT*, selected for its fluorescent properties and relatively low affinity for adsorption on particulate matter. The dye was added as a 20 per cent solution in methanol to the elutriation wash water discharge sump which rapidly drained to the outfall sewer line. Travel time in this sewer was estimated to be less than five minutes. Chlorine was not applied to the waste during the period of these tests.

The dye solution was pumped to the sewer initially at a rate of 19 milliliters per minute (ml/min.), or approximately 12 pounds of dye/day. It was intended that a constant dye addition rate be maintained throughout the 13-day dye release period. However, on two occasions sudden large fluctuations in pressure of the flushing water line connected to the discharge side of the dye feed pumps caused the pump ports to jam, and large amounts of dye were released to the estuary in a short period of time. The actual rate of dye addition

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* See disclaimer at end of paper.

is shown in Figure 2. During the test period, a total of 341 pounds of dye were used.

Since dye was added to only one segment of the estuary, the "P_i" term in each of the model equations was zero except in segment 5. In this segment the actual dye addition rate, which varied with time, as shown in Figure 2, was used as input to the model.

Observed Dye Concentrations (C_i)

During the 13-day period of the dye release, and for 21 days thereafter, dye concentrations were measured in the estuary. Measurements were made using a fluorometer (G. K. Turner & Assoc.)* which was equipped with exitation and emission light filters designed to selectively measure the fluorescence of the dye being used. With this tracer measurement system, a sensitivity of 0.01 parts per billion (ppb) may be attained.

Samples were pumped continuously from the estuary to a moving boat which carried the fluorometer. The estuary waters were pumped directly to the fluorometer which was equipped with a recorder so that a continuous record of dye concentrations was obtained for the waters through which the boat moved. The sample was withdrawn from 18 inches below the water's surface into a hollow streamlined metal strut suspended from the side of the moving boat.

Measurements were made along the complete 25-mile length of the upper segmented estuary at time of slack water. Two successive slack waters were normally measured, so that by averaging the measurements obtained at a given location, a mean value for the tidal cycle could be obtained.

In addition to this longitudinal surface sampling, dye distribution in the vertical and lateral directions was determined periodically at each of 32 cross-sections. These cross-sections were

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located at varying intervals along the length of the estuary, being more closely spaced near the dye release point. By means of this sampling network, an adequate knowledge of the temporal and spatial distribution of dye in the estuary was obtained.

The dye concentrations found in each segment through the period of the test are shown in Figures 4 - 11.

Segment Volumes (V_i)

The segment volumes were determined from the latest (1965) USCGS navigation charts for the Potomac estuary which give soundings at mean low water. The water volumes determined by planimetering these charts were increased by an appropriate amount to give estimates of mean tide level volumes. The product of these mean tide level segment volumes and the mean of the high and low water dye concentrations shown in Figures 4 - 11 gives the total mass of dye in each segment during each day of the test. No corrections were made for the small deviations of the mean tidal elevations occurring during the period of the test from the long term mean values upon which the volume calculations were based. The segment volumes used are given in Table 1.

TABLE 1

SEGMENT VOLUMES

Segment	Distance from Chain Bridge to Upper Boundary of Segment (miles)	Volume at MTL (cf x 10^{-7})
1	3.3	25.3
2	4.8	30.6
3	5.8	35.4
4	6.7	40.7
5	7.7	62.3
6	11.8	67.6
7	12.8	71.8
8	13.6	77.1
9	14.6	84.0
10	15.9	90.3
11	17.1	96.6
12	18.3	101.9
13	19.3	107.7
14	20.4	115.6
15	21.9	124.1
16	23.5	136.2
Lower Limit	25.8	

Dye Loss Rate Constant (d_i)

It was expected that some loss of dye would occur, primarily due to adsorption on bottom sediments and silt suspended in the waters of the estuary. This loss was estimated by observing the change in total dye mass in the estuary over a 20-day period immediately following the dye release period. Since dye was observed below the downstream boundary of the most seaward segment on the 15th day of the test, the sampling network was extended downstream, as necessary to assure that all of the dye in the system was being measured. The observed change in dye mass, as shown in Figure 3, appears to follow first order reaction kinetics. Determination of the slope of the line in Figure 3 yielded a reaction rate constant "d" of 0.034 per day (base e). This means that 3.4 per cent of the dye present in the estuary is lost from solution each day, equivalent to a half-life of 20.4 days. These loss rate kinetics have been observed by others[2,1] for similar dyes, although most of the reported values for "d" exceed that found in the Potomac for Rhodamine WT.

The value obtained for "d" was assumed to be constant for all segments throughout the period of the test.

Net Water Flow (Q_i)

The term "Q_i" refers to the net flow into the "i" th segment from the adjacent upstream segment, i.e., the net flow across the i-1,i or upstream boundary of the "i" th segment. Net flow in the seaward or positive direction across a boundary occurs as the net result of river inflows, waste discharges, water withdrawals, and evaporation.

For this study the inflow to the first segment was taken as the Potomac River flow reported for the U. S. Geological Survey gaging station (Leiter Gage) at Washington, D. C., adjusted for inflows and evaporation occurring in the 5.8-mile stretch of the river between the gage and the upper boundary of the first segment. The daily flow rates reported for this gage during the study period are shown in Figure 12. These flows, adjusted as described above, were assumed to occur through all segments of the upper estuary on the same day they were measured at the gage.

Losses by evaporation from the segmented portion of the estuary were subtracted from the adjusted river inflow. The daily evaporation loss was calculated for the upper estuary using Meyer's formula and data from the Washington National Airport weather station and the District of Columbia Water Quality Monitoring Station at the Woodrow Wilson Bridge. The calculated net evaporative loss reached a maximum of 400 cfs on one day of the test, but averaged 135 cfs for the 25-mile length of the upper estuary during the study period.

There are no significant withdrawals of water from the upper estuary. Daily inflows of natural drainage to each segment were calculated based on its tributary area and the average daily flow per unit area obtained from U. S. Geological Survey records for the gaging stations shown in Figure 1. A major inflow was the waste effluent from the District of Columbia Water Pollution Control Plant which discharged an average flow of 339 cfs to segment 5 during the study period. Significant waste flows from the five additional waste treatment plants shown in Figure 1 were also included. The few remaining waste flows discharged to the estuary are relatively small in volume and were disregarded.

Summing up these flows gave a net flow rate across each boundary for each day of the tracer test. Upon examination of these net flows, it was found that the inflows to the estuary (excluding the Potomac River flow and the District of Columbia waste discharge) were approximately balanced by losses due to evaporation. Therefore, in order to reduce the number of flow input functions, Q_1 through Q_5 were taken as being equal to Q_1, the adjusted Potomac River flow, and Q_6 through Q_{16} were set equal to Q_6, essentially the adjusted river flow plus the District of Columbia Water Pollution Control Plant discharge. These net advective flows are given in Table 2.

The net tidal flow into and out of each segment was assumed to be zero over a complete tidal cycle. No consideration was given to the small changes in tidal elevation and, therefore, tidal flow which occur on succeeding days during a lunar tidal cycle.

TABLE 2

CALCULATED NET ADVECTIVE FLOWS (Q_1)

Date	Day of Test	$Q_1 - Q_5$ (cfs)	$Q_6 - Q_{16}$ (cfs)
June 10		4390	4834
11	1	3884	4115
12	2	3084	3488
13	3	2761	3106
14	4	2562	2937
15	5	2384	2778
16	6	2367	2694
17	7	2377	2803
18	8	2246	2653
19	9	2235	2619
20	10	2184	2553
21	11	2173	2578
22	12	2124	2538
23	13	1883	2293
24	14	1962	2432
25	15	1932	2314
26	16	1841	2407
27	17	1790	2116
28	18	1661	2042
29	19	1431	1839
30	20	1201	1596
July 1	21	1199	1560
2	22	1109	1470
3	23	1339	1760
4	24	1374	1727
5	25	1264	1733
6	26	1397	1826
7	27	1304	1693
8	28	1168	1597
9	29	1132	1535
10	30	1150	1614
11	31	1622	3000
12	32	2946	3566
13	33	2691	3196
14	34	2096	2570

Turbulent Exchange Factor (E_i)

The turbulent exchange factor "E" is calculated for each segment boundary from the expression:

$$E_i \text{ (cf/day)} = \frac{K_i A_i}{0.5 (L_i + L_{i-1})} \quad (2)$$

where the "i" subscript refers to the boundary between segments i-1 and i, "K" is the longitudinal dispersion coefficient (analogous to the classical Fickian diffusion coefficient, expressed in areal units per day), "A" is the cross-sectional area of the boundary plane, and "L" is the segment length.

The above expression is based on Fick's first law of diffusion, i.e.,

$$N_i \text{ (lb/sf/day)} = K \frac{dC}{dx} \quad (3)$$

where "N" is the rate of mass transfer of substance per unit area across a boundary where the spatial gradient of the substance is "dC/dx" ("C" is in lbs/cf) and "K" is defined as above.

If the mean concentration in two adjacent segments is assumed to occur at their midpoints, and the gradient between these midpoints is linear, it can be shown by geometry that:

$$\frac{dC}{dx} = \frac{C_{i-1} - C_i}{0.5 (L_{i-1} + L_i)} \quad (4)$$

Substituting (4) into equation (3) gives:

$$N_i \text{ (lbs/sf/day)} = \frac{K (C_{i-1} - C_i)}{0.5 (L_{i-1} + L_i)} \quad (5)$$

Multiplying equation (5) by the cross-sectional area across which the turbulent exchange takes place, yields the mass flow rate "D_i":

$$D_i \text{ (lbs/day)} = \frac{A_i \, K_i \, (C_{i-1} - C_i)}{0.5 \, (L_{i-1} + L_i)} \tag{6}$$

Substituting equation (2) into (6) yields:

$$D_i = E_i \, (C_{i-1} - C_i) \tag{7}$$

which is the expression used in equation (1) to describe the mass flow of substance across a boundary due to turbulent exchange.

The "E" term, or more specifically "K" was the unknown parameter which the study was designed to evaluate. The "K" term as used herein is defined as the coefficient of longitudinal dispersion. This term applies to net longitudinal mass transport resulting not only from turbulent diffusion but also from velocity and concentration variations in a cross-section. The latter effect has been shown[5] to be of greater significance in estuary type flows. It has been assumed that dispersion is analogous to Fickian diffusion with the diffusion coefficient replaced by a dispersion coefficient.

As mentioned previously, initial values of "K" were assumed for each boundary. These values were then adjusted to obtain good agreement of the model output with the dye concentrations observed in the estuary. The initial values were chosen on an empirical basis[4] and ranged from 1.5 sq mi/day for the boundaries at the upper end of the estuary to 5.9 sq mi/day at the lowest boundary.

Proportionality Factor (ξ_i)

The proportionality factor "ξ_i" is used in the first two terms of equation (1) that describe the advective movement of dye into and out of a segment. This mass movement across the i-1,i boundary due to advection may be expressed simply as the product of the net advective flow "Q_i" and the concentration at the boundary. However, since only the average concentration of the adjacent segments are considered in the model, the concentration at the boundary must be calculated. It can be shown by geometry that for the case of a linear gradient between the midpoints of two adjacent segments, the concentration at the boundary is given by the first two terms in brackets in equation (1) where:

$$\xi_i = \frac{L_i}{L_{i-1} + L_i} \tag{8}$$

Equation (8) gives a satisfactory first approximation for the proportioning factor applicable to the i-1,i boundary. To assure a realistic solution, however, the following relationship must be observed:

$$\xi > 1 - \frac{E}{Q} \tag{9}$$

To simplify computations where "E" was changed frequently, the inequality given by (9) was treated as an equality. So long as the proportionality factor "ξ" remains within the lower limit defined by equation (9) and an upper limit of unity, the solutions obtained by the model are relatively insensitive to the value chosen for "ξ."

ANALOG SIMULATION

The set of sixteen differential equations similar to equation (1) were programed on an EAI* 231-R analog computer, pictured in Figure 13. The output selected from the computer was a record of concentration versus time for each of the sixteen segments of the estuary. These calculated concentration-time histories were automatically plotted as a continuous ink trace on graph paper, as shown in Figures 4 - 11. The other two lines on these plots describe dye concentrations observed in each segment at high and low slack water. Repeated solutions were obtained by the computer for each different set of "K" values supplied as input. The objective of each succeeding run was to bring the ink trace output of the computer closer to a point midway between the observed high and low slack water values. The set of "K" (and associated "ξ") values which gave the best fit are shown in Table 3.

In carrying out such computations, it is necessary to specify the proper initial and boundary conditions for the test. Prior to the start of the dye release there is, of course, no dye present in the estuary and the "C_i's" are all initially set to zero. For the upper and lower boundaries of the system, the concentration-time histories actually observed were used as the boundary condition input function. Since no dye was ever found at the upper boundary of segment 1, the upper boundary condition was zero throughout the test.

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* See disclaimer at end of paper.

The lower boundary condition was likewise zero until the 15th day of the test when dye was found there. The dye concentration at the lower boundary then gradually increased over the succeeding twelve days when a relatively steady level was maintained for the remainder of the test period.

TABLE 3

MODEL PARAMETERS

FINAL ANALOG COMPUTATION

i	K_i (sq mi/day)	ξ_i
1	0	1.0
2	0.2	0.95
3	0.2	0.94
4	0.2	0.92
5	0.25	0.93
6	0.3	0.5
7	0.3	0.88
8	0.4	0.70
9	0.4	0.94
10	0.6	0.88
11	0.6	0.77
12	0.6	0.88
13	0.6	0.84
14	0.6	0.85
15	0.6	0.87
16	0.6	0.89
17	0.6	0.89

DISCUSSION

In general, the final curves obtained as output from the analog computer correspond satisfactorily with the observed data. Good agreement was obtained for the segments at and near the discharge point during the dye release period when changes in dye concentration took place most rapidly. In the six segments just below the discharge point, there was an obvious tendency for the computed concentrations to drop off faster toward the end of the test than was actually observed. No reasonable manipulation of the dispersion coefficients was capable of eliminating this anomaly. It was concluded that this effect was produced by the two large instantaneous dye releases which occurred midway through the dye discharge period, as shown in Figure 2. Quite possibly, some significant portion of this large amount of dye was trapped in the coves and inlets along the shoreline near the release point. This entrapped dye could then have fed slowly back into the main channel of the estuary and thereby maintained higher dye concentrations for a longer period of time than otherwise would have occurred. This effect has also been observed in hydraulic model studies when instantaneous dye releases were carried out.[6]

The variations in river flow during the study period and the superposition of the two instantaneous releases upon a continuous release provided a rather severe simulation test for the mathematical model. In spite of this, the degree of agreement between calculated

and observed dye concentrations leads to the conclusion that the model with the estuarial dispersion properties as finally established can be expected to describe the distribution of soluble pollutants in the Potomac estuary with a reasonable degree of accuracy.

During the initial simulations on the analog computer, it was apparent that good agreement would not be possible near the discharge point with the segment sizes originally employed. It was necessary to enlarge segment five which received the dye discharge to approximately three times its original size to achieve meaningful results. The reason for this is related to the water movement occurring during a tidal cycle. Dye added as a continuous discharge to oscillating tidal waters will be rapidly distributed above and below the release point during a single tidal cycle over a distance equivalent to a tidal excursion, or about 4 miles in this case. This distribution, of course, is not related to advection or dispersion, but simply to the physical movement of the receiving waters themselves. A similar effect could be achieved by visualizing the receiving water as being stationary while the discharge pipe moved upstream and downstream a total distance equivalent to a tidal excursion. It would be possible to account for this effect in the model in a similar manner by distributing the tracer inflow to adjacent segments above and below the outfall. However, this procedure was not used and instead, the segment to which the tracer was discharged was enlarged to half the tidal excursion distance in both the upstream and downstream directions.

The range of dispersion coefficients finally determined, 0.2 to 0.6 square miles/day, were significantly lower than those commonly calculated from observed chloride distributions in more brackish waters. This is in agreement with the findings of Harleman[3] and others that the dispersion coefficients found in saline waters are strongly influenced by longitudinal density currents. This circulatory movement which occurs where vertical salinity gradients exist is the result of upstream movement of the denser bottom waters and downstream flow of the less saline surface waters. This type of gravitational circulation would tend to be reflected in higher dispersion coefficients in the classical advection-diffusion model such as employed in this study.

Estuary chloride concentrations measured during the tracer test are shown in Figure 14. The low concentrations of chlorides measured in the study area indicate that the density current effects mentioned above would not be expected in the upper Potomac estuary during the test period. Since salinity steadily increases downstream toward the Bay, a downstream rise in the dispersion coefficient might also be expected. This was the case, as shown in Figure 15. The higher values shown for the estuary below the point where the tracer study terminated were obtained from analysis of historical chloride records using a digital computer solution of the model. The solid line in Figure 15 represents a visual approximation of a line of best fit to both sets of data and will be used in future calculations requiring solution of the model. The dramatic change in the value

of the dispersion coefficient over the upper forty miles of the Potomac estuary illustrates the hazards involved in extrapolating brackish water dispersion phenomena to tidal fresh waters.

The knowledge of dispersion characteristics of the upper Potomac estuary which was gained in this study will permit the mathematical model described previously to be used with a reasonable degree of confidence in the analysis of water pollution control problems. One such use, for example, would be an examination of the influence of river inflow upon the distribution of pollutants in the estuary. Using the dispersion coefficients described by the smooth curve in Figure 15, a digital solution of the model for various rates of fresh water inflow produced the family of curves shown in Figure 16. The same set of dispersion coefficients was used for each river inflow investigated, since it is not known to what extent the magnitude of net advective flow may affect the value of the dispersion coefficient. These effects, however, are not believed to be significant over the range of flows shown in Figure 15, based on their relatively small contribution to the total tidal flow which is experienced in the estuary.

In these calculations, the pollutant was assumed to enter the estuary ten miles below Chain Bridge, which is the location of the District of Columbia Water Pollution Control Plant effluent discharge. The pollutant is non-conservative with a first-order decay rate constant of 0.23 per day (base e) comparable to the rate of exertion of

the biochemical oxygen demand of organic materials in waste effluents. A waste flow of 350 cfs also enters the estuary at the pollutant discharge point. The conditions depicted are those which would exist at steady state.

Figure 16 shows that the magnitude of pollutant concentrations in the estuary is influenced by the amount of flow entering from the Potomac River, and that this influence varies depending upon the distance below the head of the estuary. This type of information, of course, is extremely useful in conducting a rational examination of the benefits of flow regulation as well as various other pollution control measures which must be considered before the optimum program can be selected.

CONCLUSIONS

1. The segmented estuary model satisfactorily describes the distribution of an artificially introduced tracer in the upper 25 miles of the Potomac estuary and, similarly, can be used to predict the distribution of soluble pollutants which may be introduced in this area.

2. The turbulent dispersion characteristics found during the period of this study are best described by coefficients which increase from 0.2 sq mi/day near the head of tide to about 1.0 sq mi/day at a distance of 25 miles downstream.

3. The loss rate of Rhodamine WT dye found in the relatively fresh waters of the upper Potomac estuary can be described by a first order reaction rate constant of 0.034.

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* Mention of products and manufacturers is for identification only and does not imply endorsement by the Federal Water Pollution Control Administration and the U. S. Department of Health, Education, and Welfare.

ACKNOWLEDGMENT

The cooperation and assistance rendered by Messrs. A Fay and H. Schreiber of the District of Columbia Department of Sanitary Engineering were invaluable to the conduct of this study and are gratefully acknowledged.

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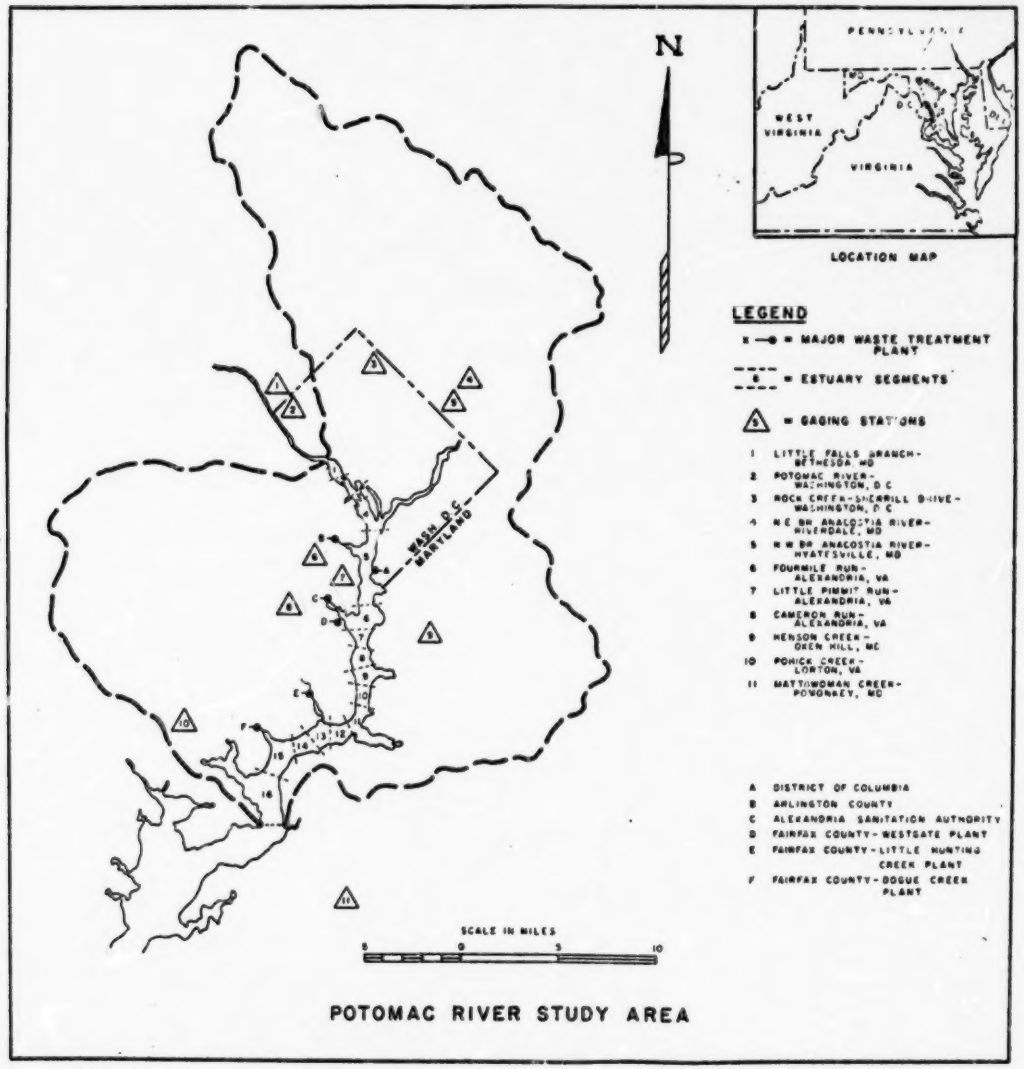


POTOMAC RIVER STUDY AREA

FIGURE 1

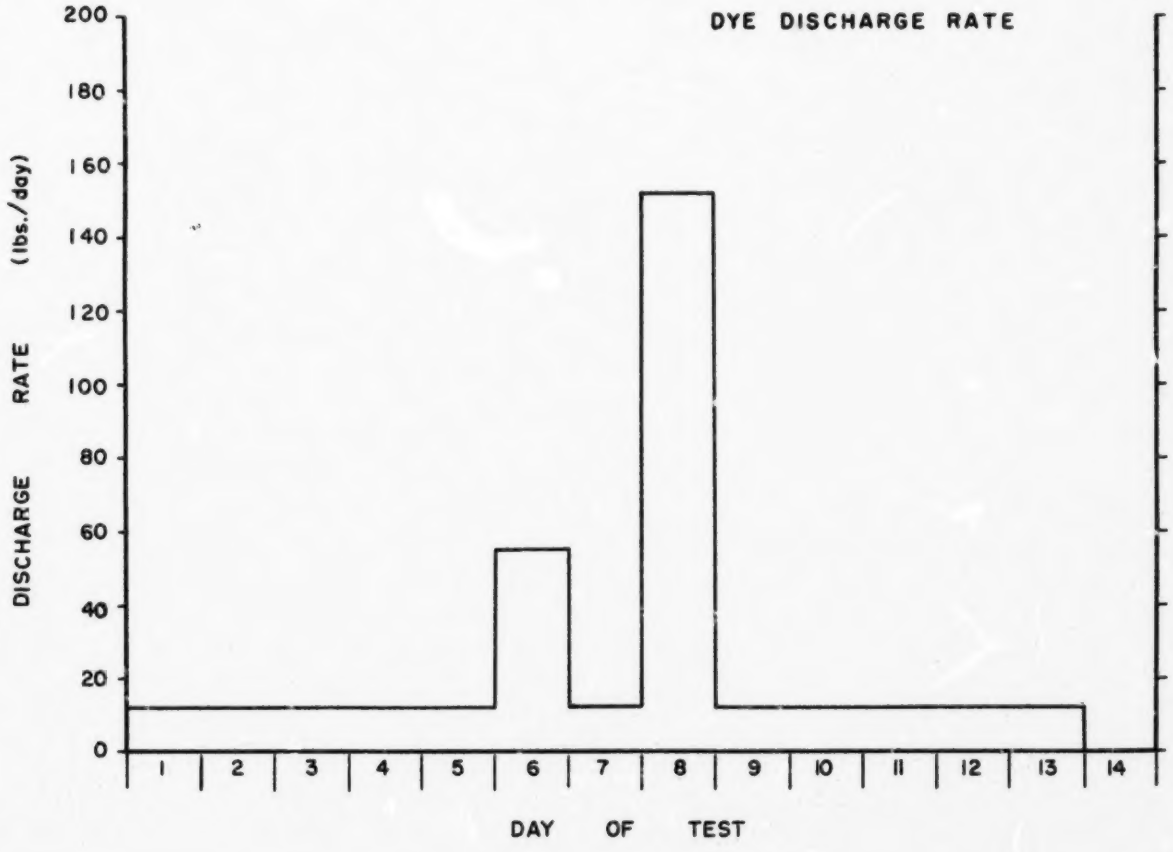

DYE DISCHARGE RATE
DISCHARGE RATE (lbs./day)
200
180
160
140
120
100
80
60
40
20
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
DAY OF TEST

FIGURE 2

DYE LOSS RATE

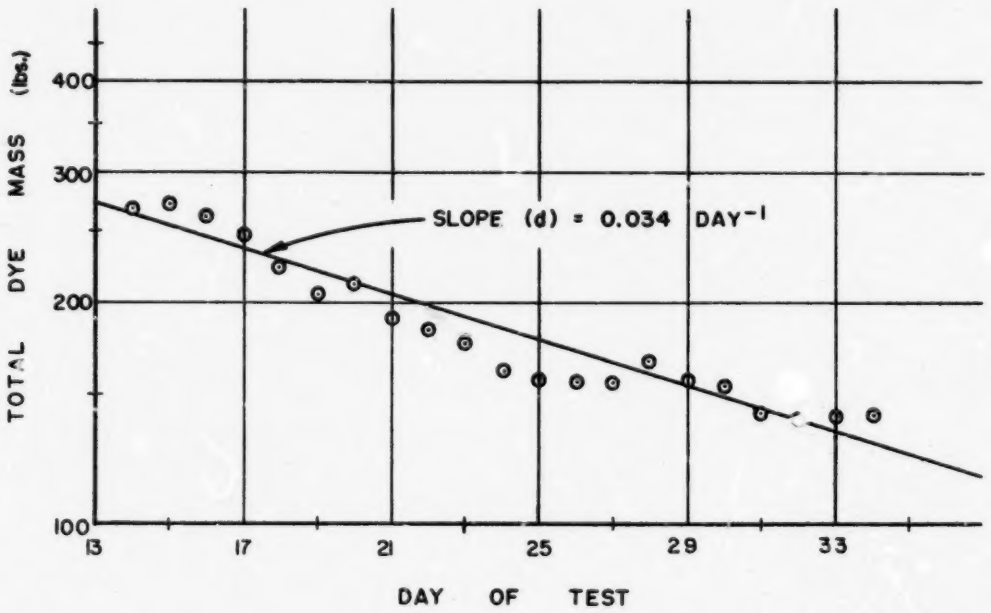


FIGURE 3

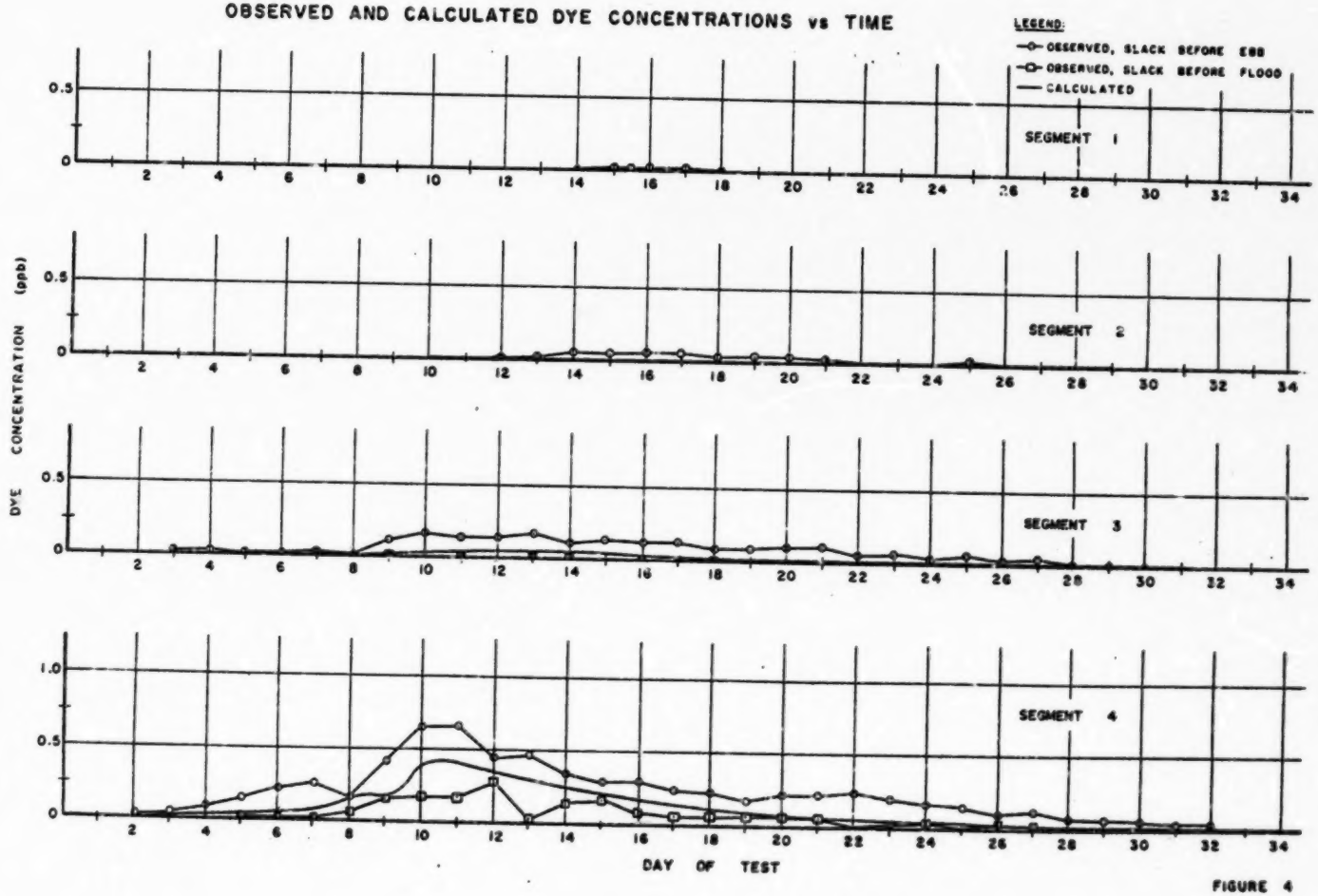

OBSERVED AND CALCULATED DYE CONCENTRATIONS vs TIME
LEGEND:
OBSERVED, SLACK BEFORE EBB
OBSERVED, SLACK BEFORE FLOOD
CALCULATED
SEGMENT 1
SEGMENT 2
SEGMENT 3
SEGMENT 4
DYE CONCENTRATION (ppb)
DAY OF TEST

FIGURE 4

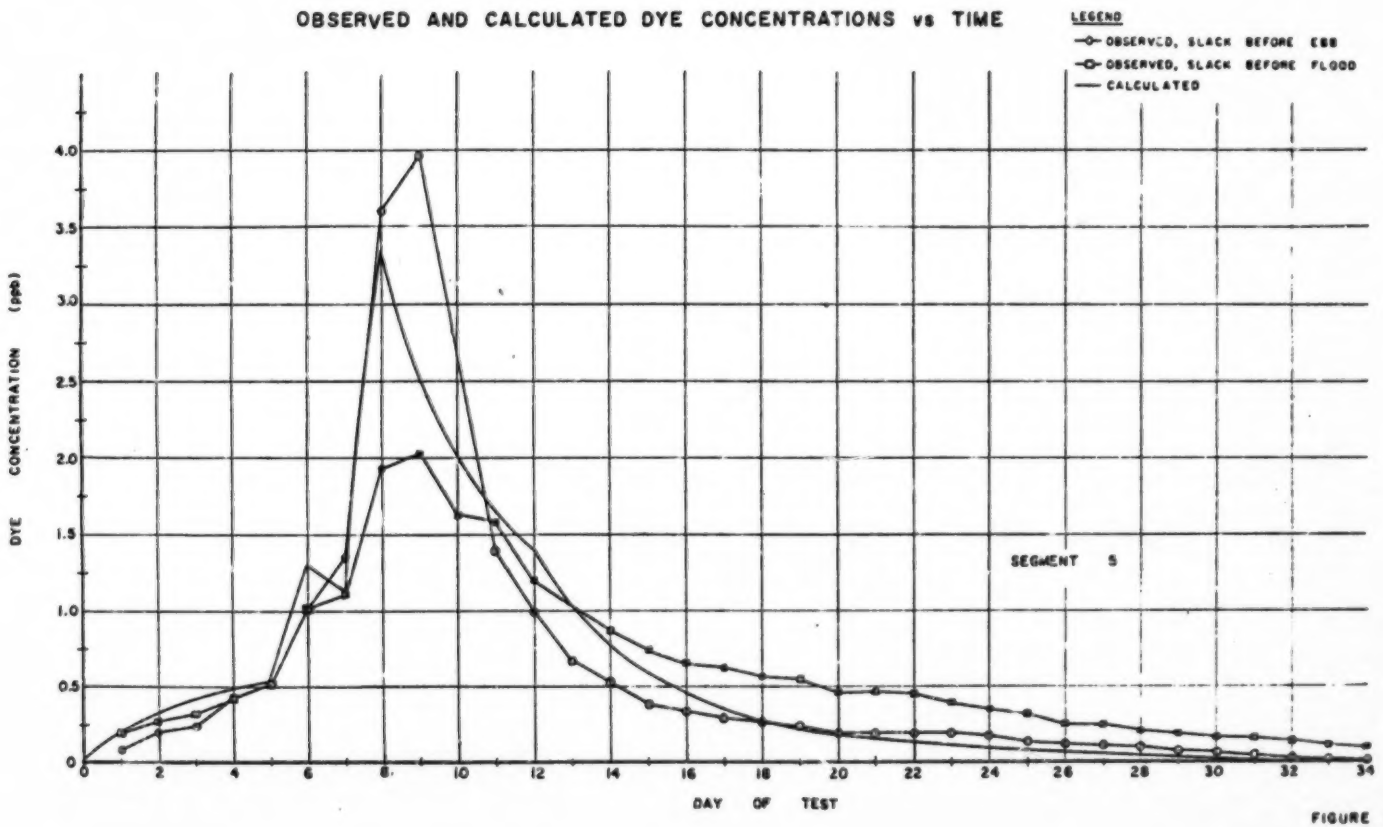

OBSERVED AND CALCULATED DYE CONCENTRATIONS vs TIME
LEGEND
OBSERVED, SLACK BEFORE EBB
OBSERVED, SLACK BEFORE FLOOD
CALCULATED
DYE CONCENTRATION (ppb)
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
32
34
DAY OF TEST
SEGMENT 5

FIGURE 5

OBSERVED AND CALCULATED DYE CONCENTRATIONS vs TIME

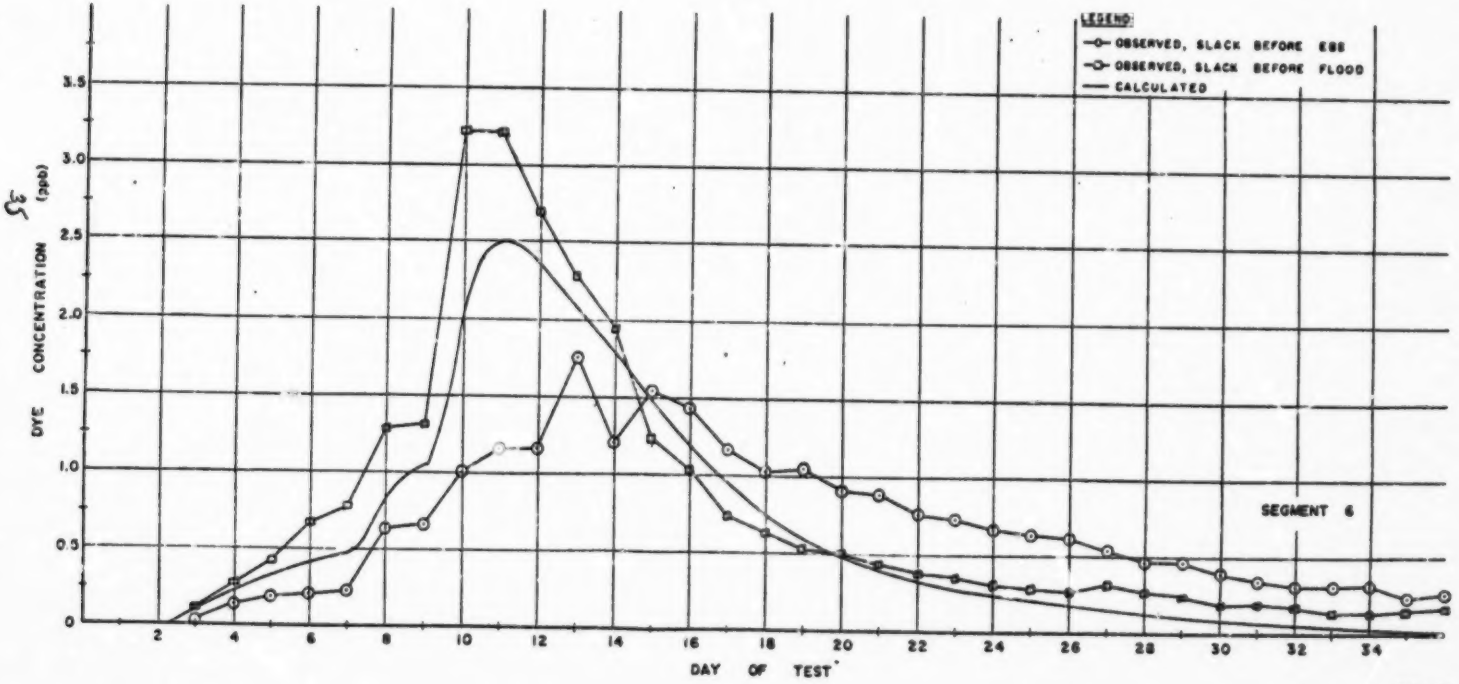


FIGURE 6

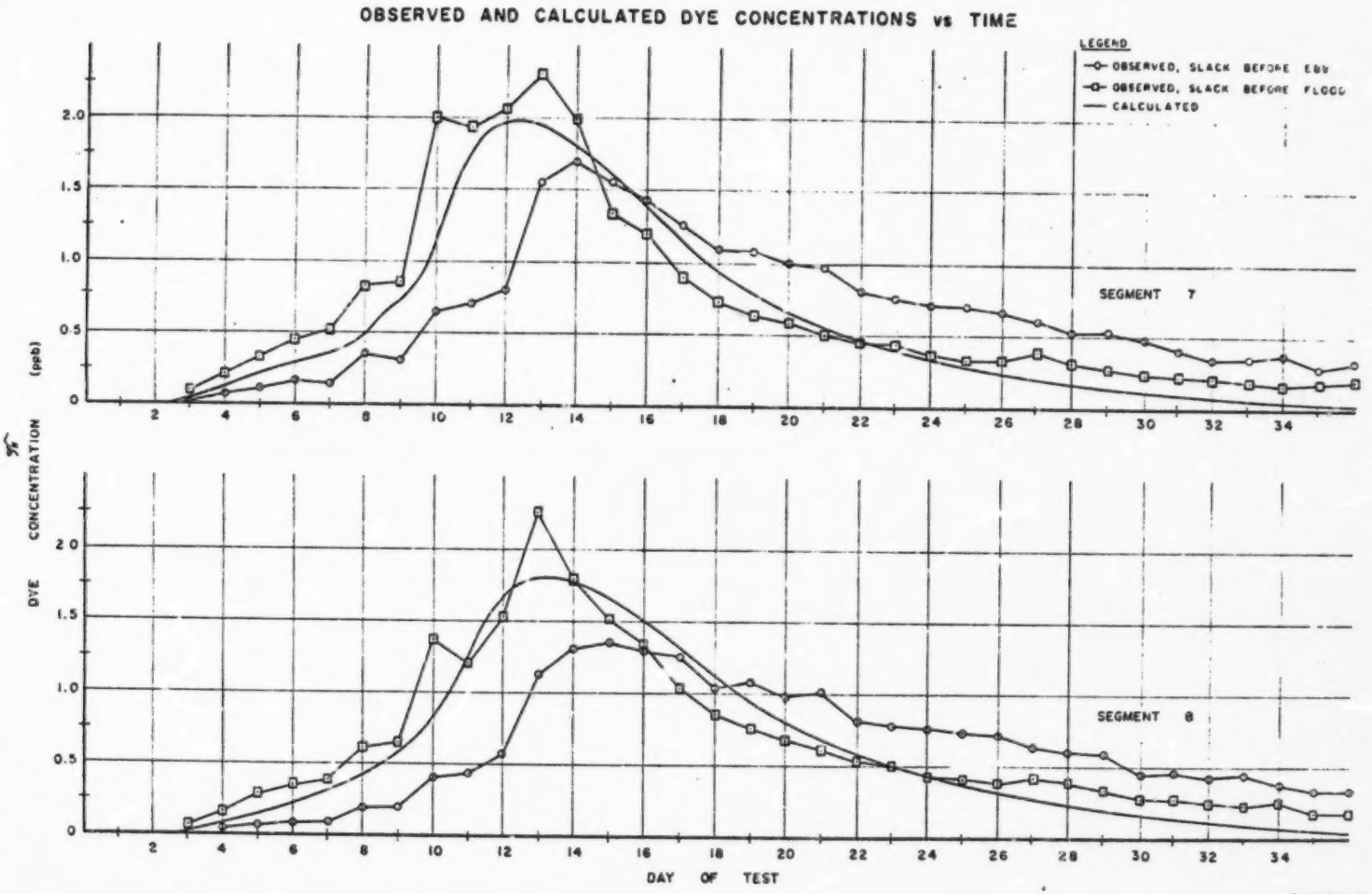

OBSERVED AND CALCULATED DYE CONCENTRATIONS vs TIME
LEGEND
OBSERVED, SLACK BEFORE EBB
OBSERVED, SLACK BEFORE FLOOD
CALCULATED
SEGMENT 7
SEGMENT 8
DYE CONCENTRATION (ppb)
DAY OF TEST
0
0.5
1.0
1.5
2.0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
32
34

FIGURE 7

OBSERVED AND CALCULATED DYE CONCENTRATIONS vs TIME

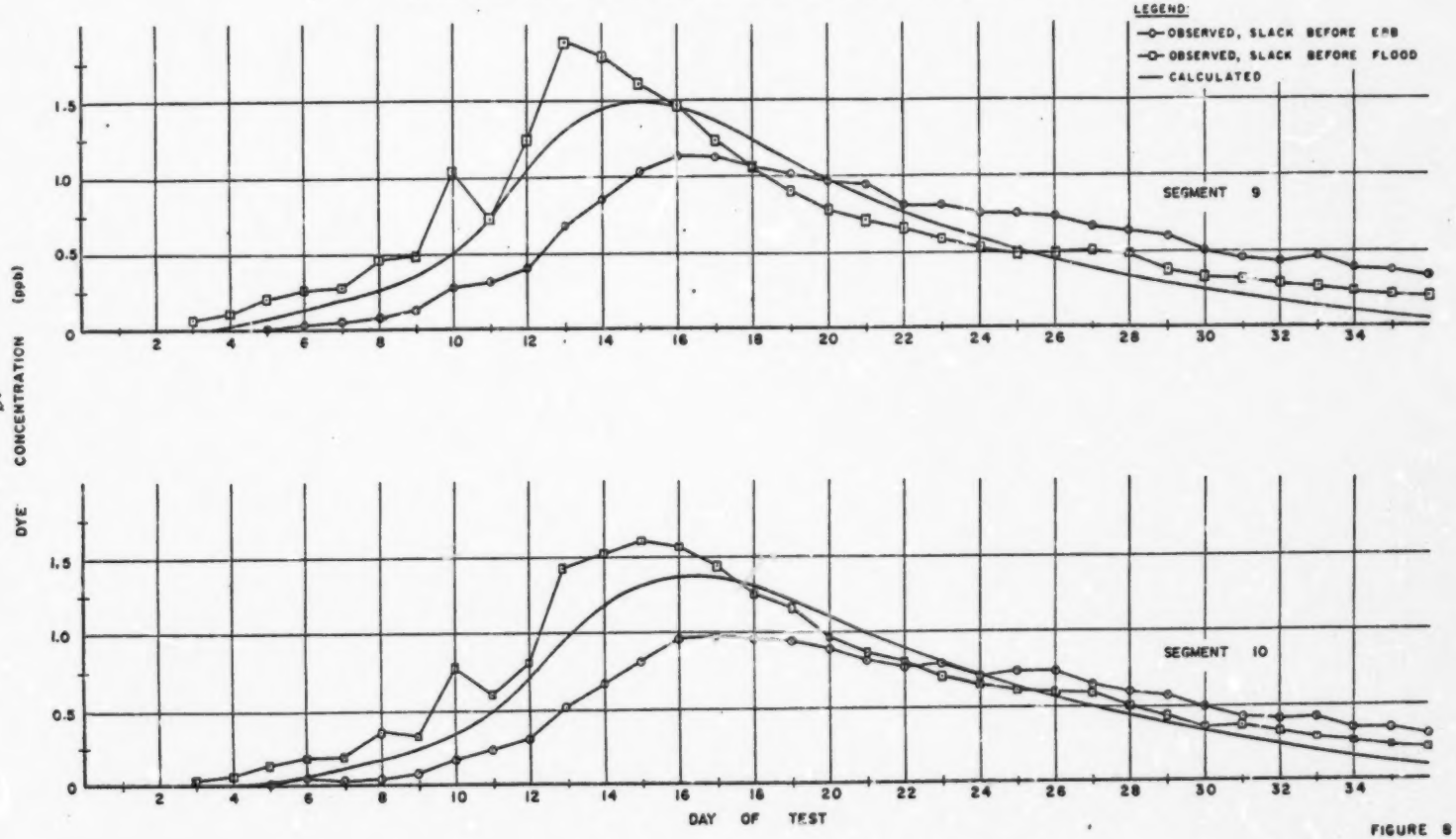


FIGURE 8

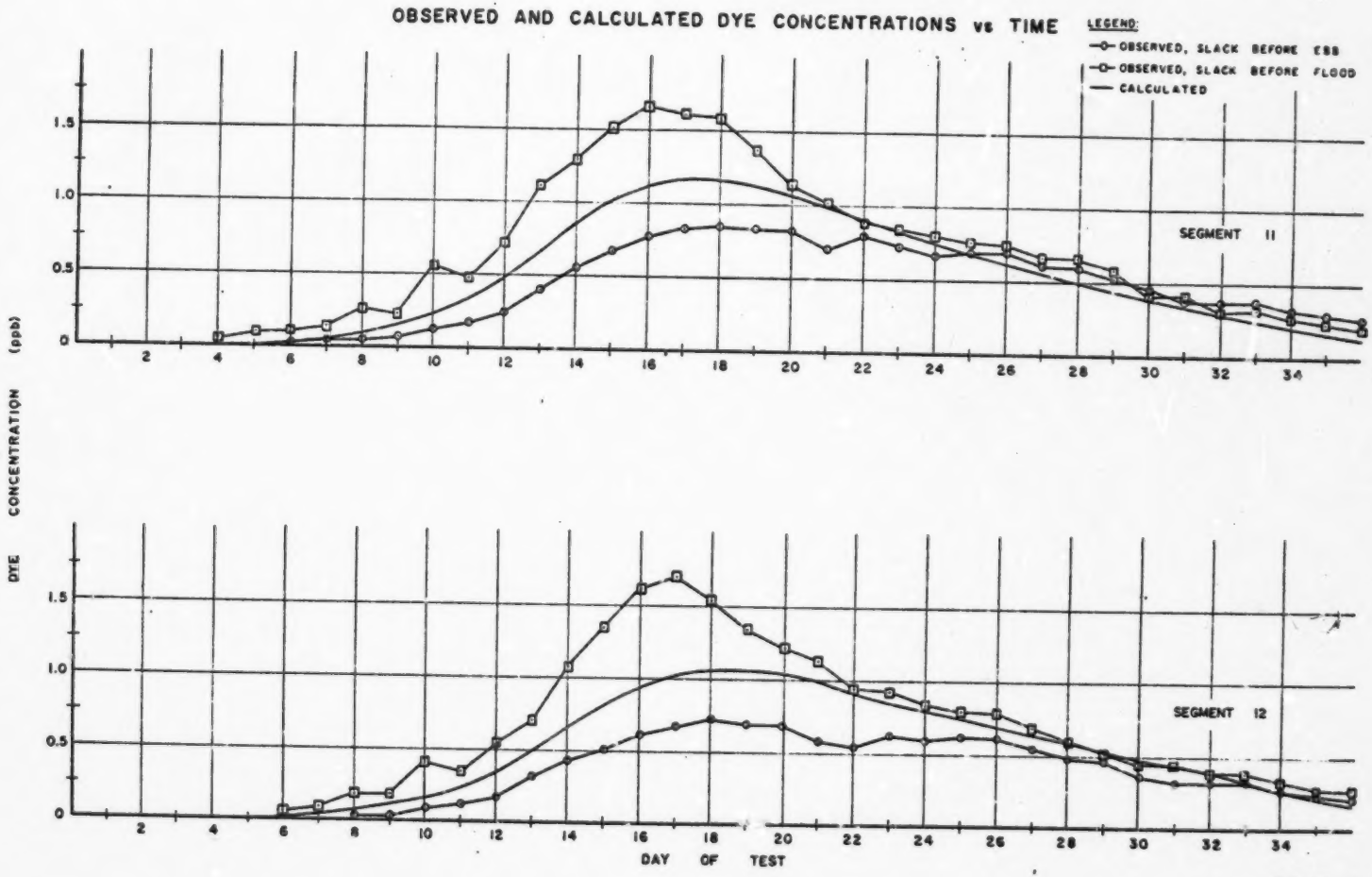

OBSERVED AND CALCULATED DYE CONCENTRATIONS vs TIME
LEGEND:
OBSERVED, SLACK BEFORE EBB
OBSERVED, SLACK BEFORE FLOOD
CALCULATED
SEGMENT 11
SEGMENT 12
DYE CONCENTRATION (ppb)
DAY OF TEST
0
0.5
1.0
1.5
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
32
34

FIGURE 9

OBSERVED AND CALCULATED DYE CONCENTRATIONS vs TIME

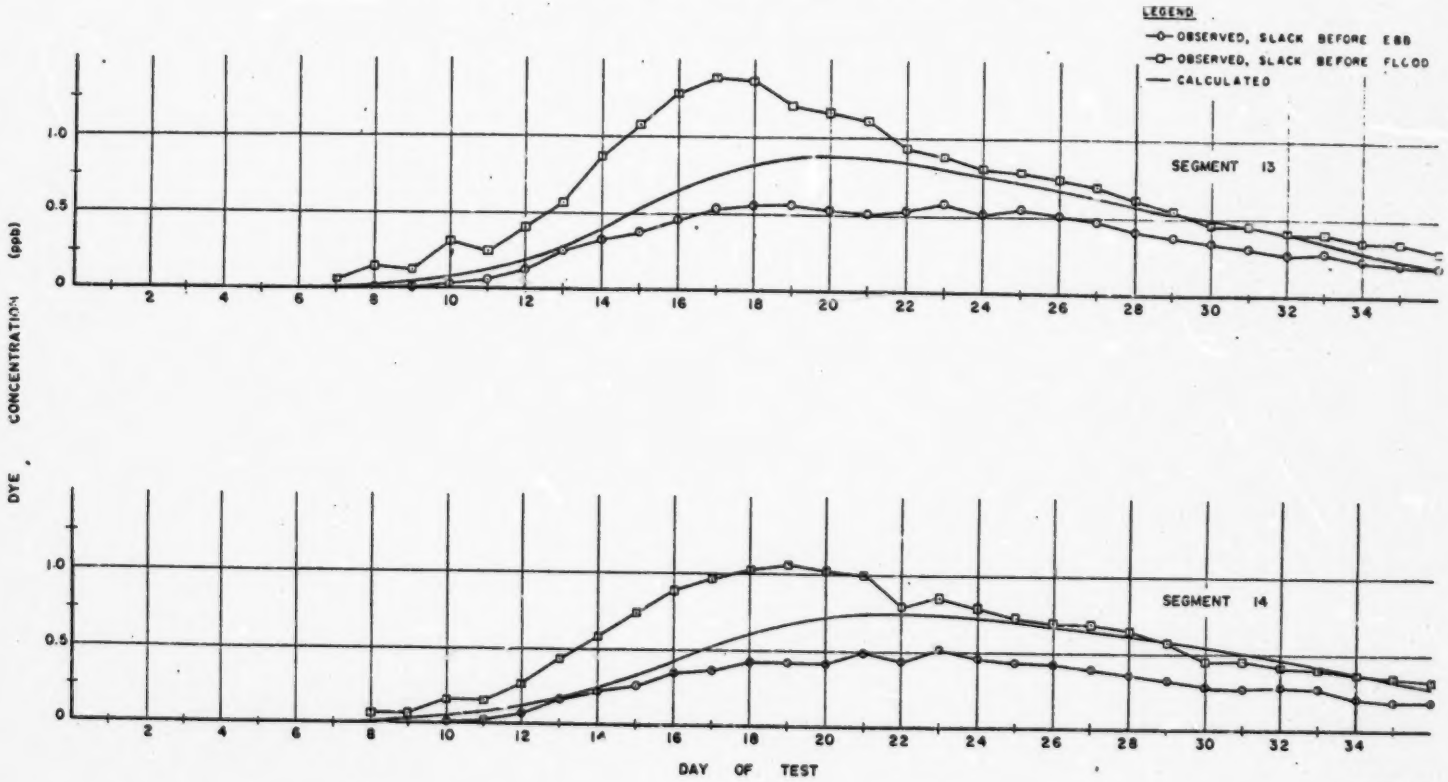


FIGURE 10

OBSERVED AND CALCULATED DYE CONCENTRATIONS vs TIME

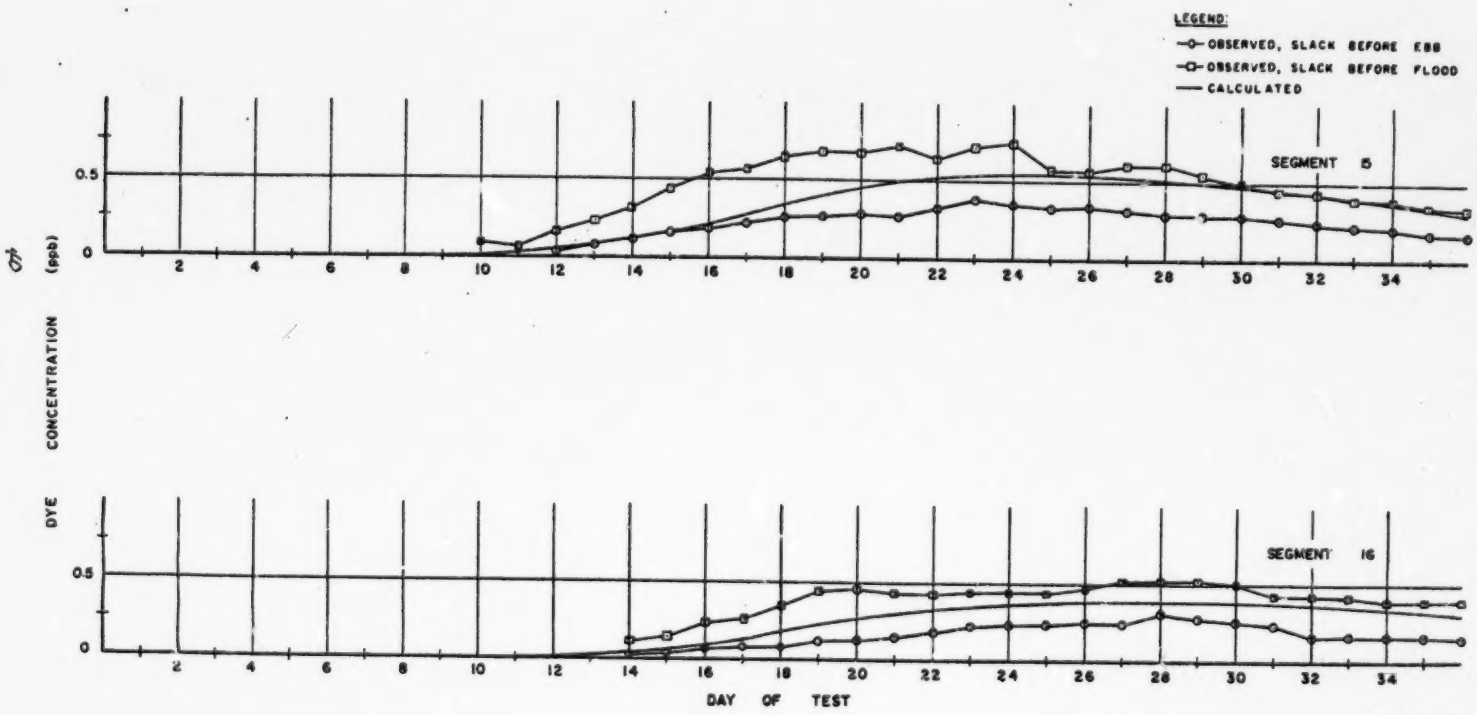
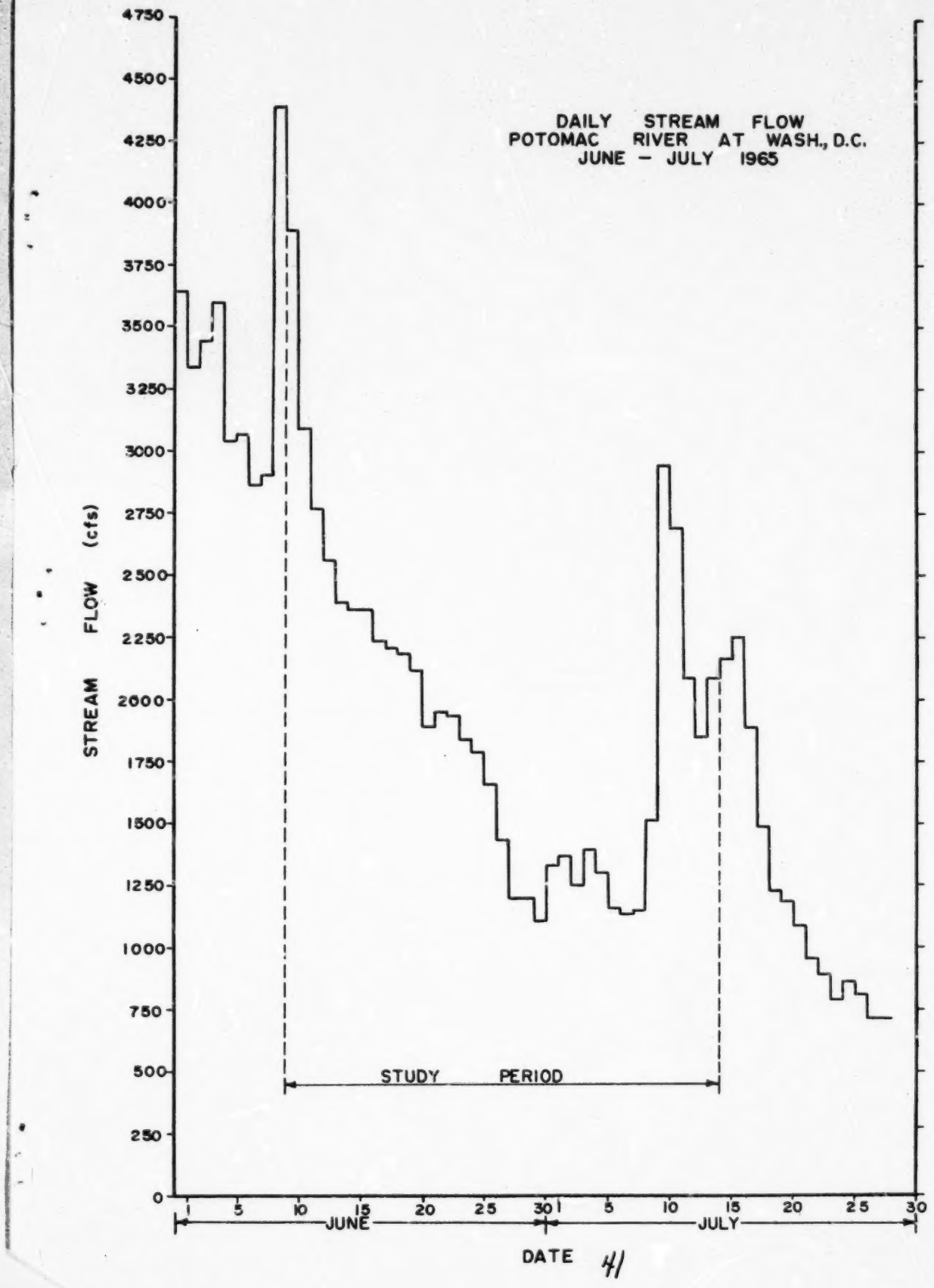
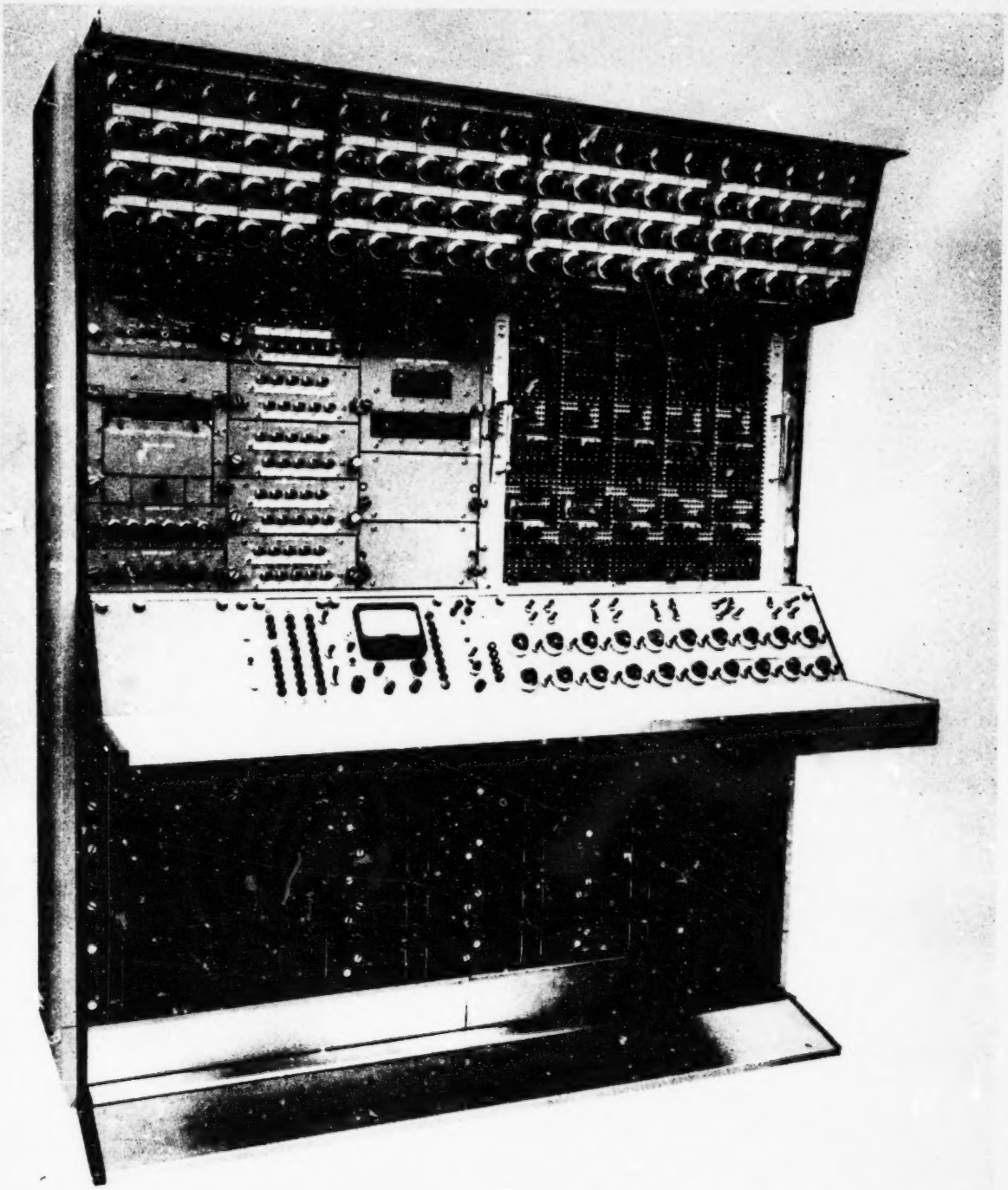


FIGURE 11


DAILY STREAM FLOW
POTOMAC RIVER AT WASH., D.C.
JUNE – JULY 1965
STREAM FLOW (cfs)
4750
4500
4250
4000
3750
3500
3250
3000
2750
2500
2250
2000
1750
1500
1250
1000
750
500
250
0
STUDY PERIOD
1
5
10
15
20
25
30
1
5
10
15
20
25
30
JUNE
JULY
DATE

41

FIGURE 12



120 Amplifier PACE Model 231-R

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FIGURE 13

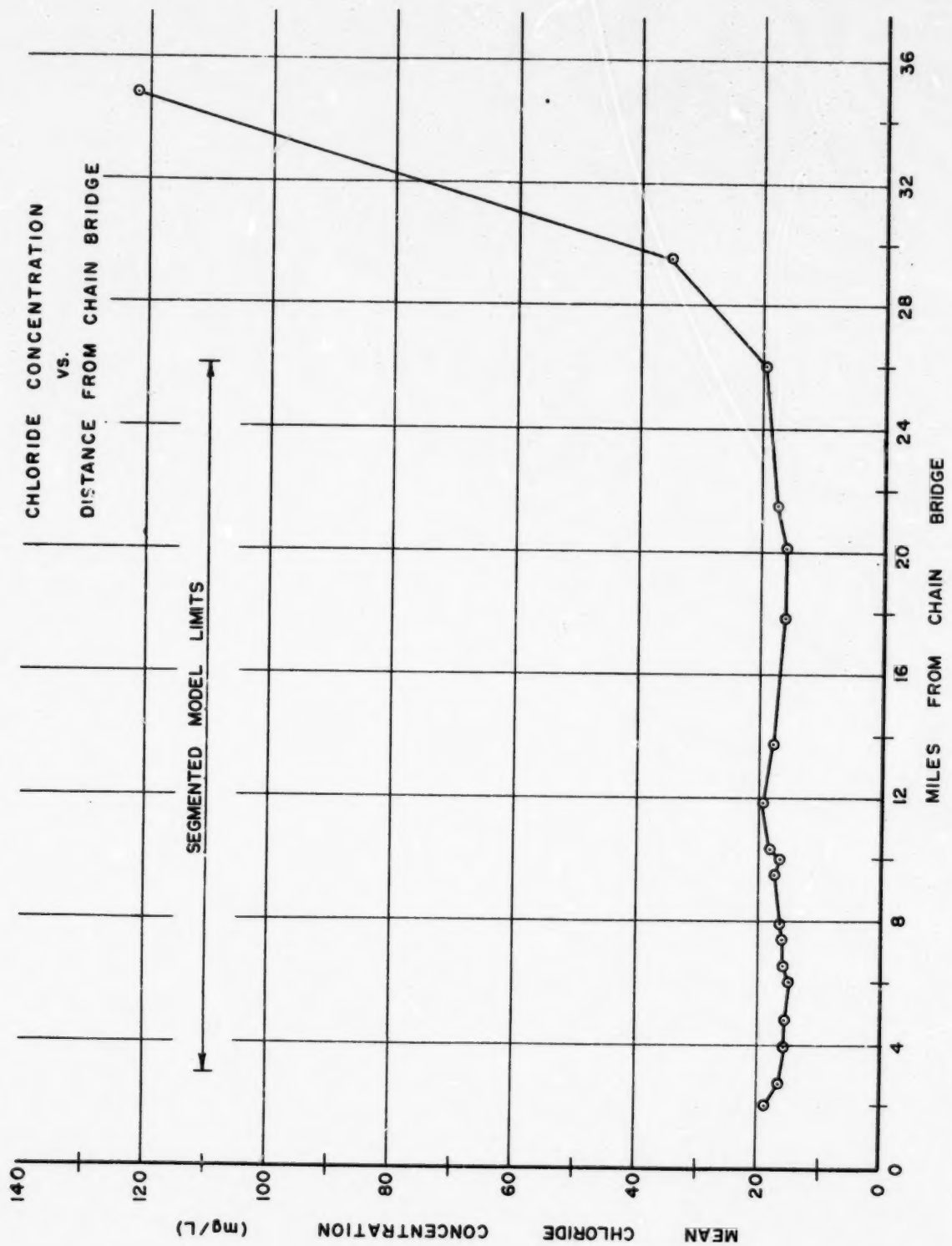
CHLORIDE CONCENTRATION
VS.
DISTANCE FROM CHAIN BRIDGE
SEGMENTED MODEL LIMITS
MEAN CHLORIDE CONCENTRATION (mg/L)
MILES FROM CHAIN BRIDGE
140
120
100
80
60
40
20
0
0
4
8
12
16
20
24
28
32
36

FIGURE 14

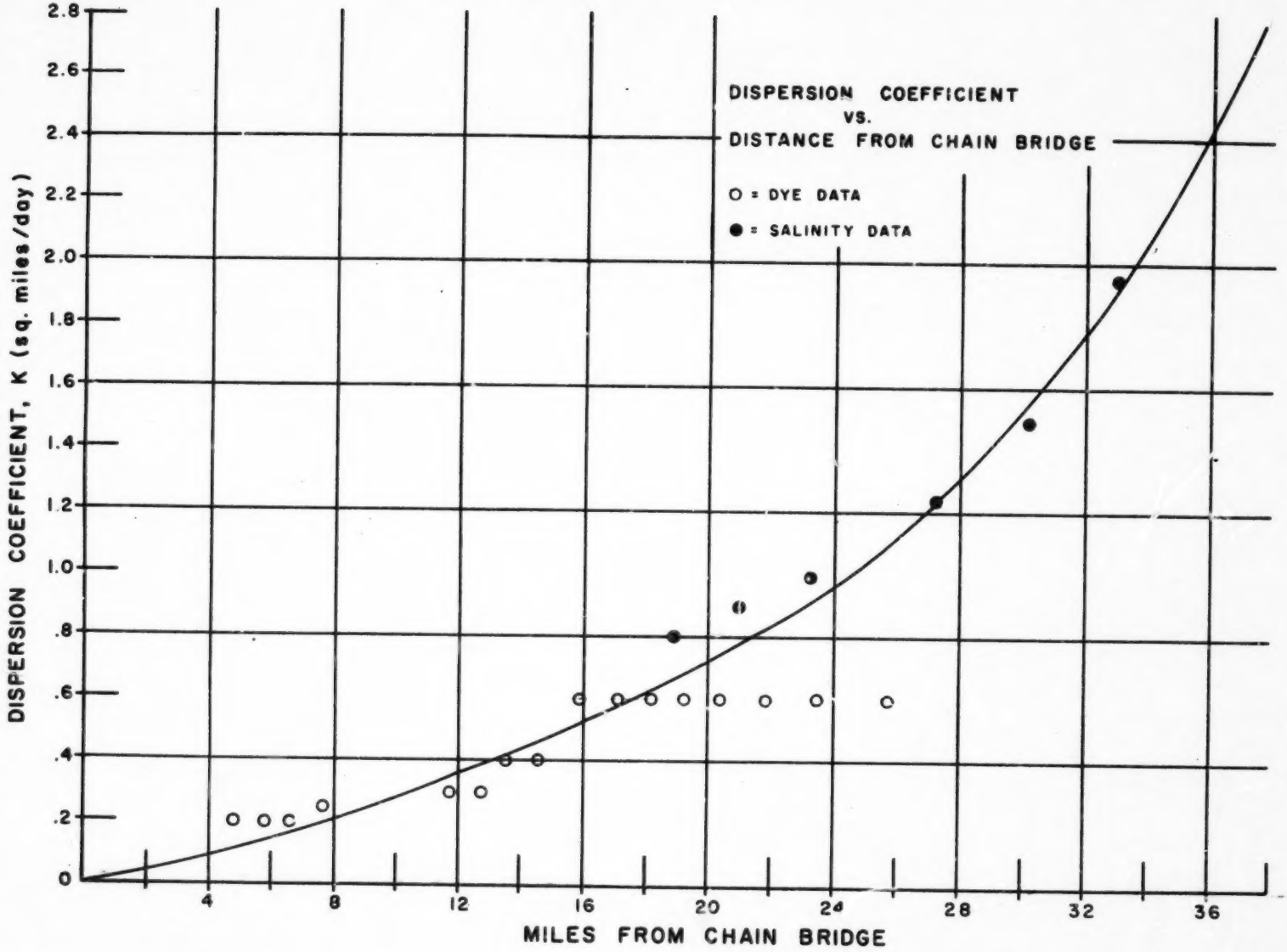
DISPERSION COEFFICIENT
VS.
DISTANCE FROM CHAIN BRIDGE
O = DYE DATA
● = SALINITY DATA
DISPERSION COEFFICIENT, K (sq. miles/day)
MILES FROM CHAIN BRIDGE
0
.2
.4
.6
.8
1.0
1.2
1.4
1.6
1.8
2.0
2.2
2.4
2.6
2.8
4
8
12
16
20
24
28
32
36

FIGURE 15

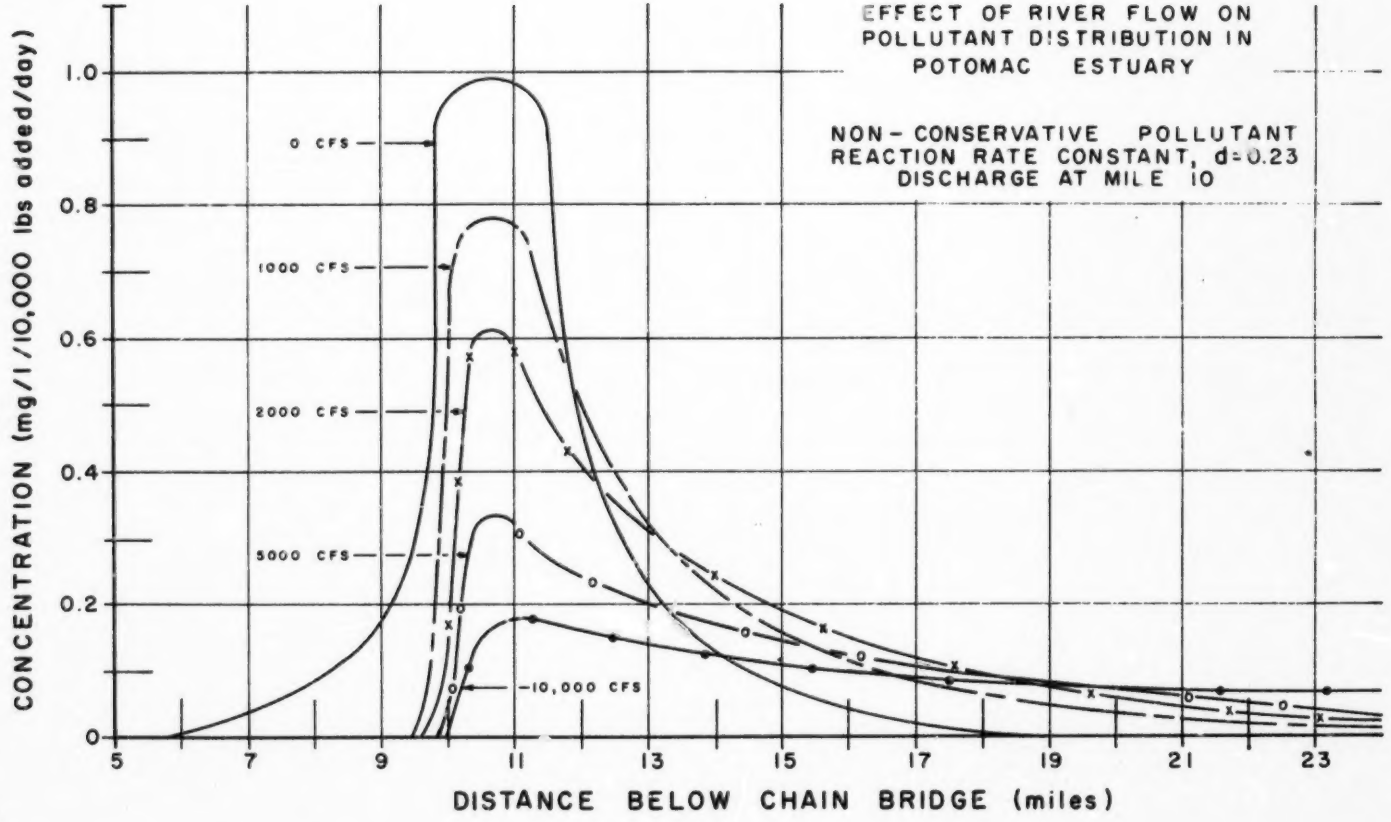
EFFECT OF RIVER FLOW ON
POLLUTANT DISTRIBUTION IN
POTOMAC ESTUARY
NON-CONSERVATIVE POLLUTANT
REACTION RATE CONSTANT, d=0.23
DISCHARGE AT MILE 10
0 CFS
1000 CFS
2000 CFS
5000 CFS
10,000 CFS
CONCENTRATION (mg/l/10,000 lbs added/day)
DISTANCE BELOW CHAIN BRIDGE (miles)
0
0.2
0.4
0.6
0.8
1.0
5
7
9
11
13
15
17
19
21
23

FIGURE 16